An in-plane tensile test for rheological and formability identification : comparison between experimental and numerical FLC

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Abstract. Both accurate constitutive laws and formability limits of materials are essential for a numerical optimization of sheet forming processes. To identify these behaviors, experimental databases are needed. In this work, experiments are performed from a biaxial device able to give for a unique in-plane specimen a good prediction of rheological parameters and formability. The proposed device is a servo-hydraulic testing machine provided with four independent dynamic actuators. By localizing necking in the central zone of the specimen, the strain path in this zone is controlled by the speed ratio between the two axes and the whole forming limit diagram can be covered. The experimental forming limit curve for the aluminium alloy AA5086 is determined thanks to a rigorous procedure for detecting the onset of necking in the specimen. Material parameters (constants of both hardening law and anisotropic yield criterion) are identified from the global measurement of force versus displacement curves by means of an inverse analysis procedure. Comparison between experimental and numerical forming limit curves are presented. For the numerical FLCs, two sets of material parameters are compared, the former is identified through the classical uniaxial test and the latter thanks to the dedicated cruciform specimen.

Keywords: Biaxial testing, cruciform specimens, forming limit diagram, rheological behavior
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INTRODUCTION

Metal forming operations are carried out under multi-axial states of stress, then limiting the mechanical behavior identification of materials to uniaxial tensile tests can lead to a misrepresentation of this behavior. The use of a more realistic loading during identification tests such as biaxial loading conditions must lead to a more accurate representation of the expected behavior of the material. For the evaluation of formability, the well-known method consists in plotting a Forming Limit Diagram (FLD) for a given material. In order to overcome the drawbacks of the classical tests, like Marciniak test or Nakazima test, a cruciform specimen can be an interesting alternative if the strain path at the onset of necking is directly controlled by the testing speed of each actuator of the biaxial machine, independently from the specimen shape and without any friction effects. Moreover, this device is well adapted to make tests under dynamic conditions and then evaluate the effect of strain rate on formability of materials. Indeed, strain rate sensitivity has been identified as an important factor for determining formability and can alter significantly the level and shape of forming limit curves. However, to date, very few studies have been done to characterize the forming behavior of sheet metals in a large range of strain rates, mainly due to a lack of reliable experimental data.

In this study, a servo-hydraulic testing machine provided with four independent actuators is used to realize in-plane biaxial tensile tests on sheet specimens. For this biaxial test, a dedicated cruciform specimen shape has been designed and optimized. Then, an aluminium alloy (AA5086) has been tested to identify from the same specimen both formability limits and whole elasto-plastic behavior, including hardening law and anisotropic yield criterion [1]. In order to validate this material identification, a comparison is proposed with the classical method which consists in testing three uniaxial specimens, in rolling, transverse and 45° directions. The accuracy of the two approaches is evaluated through the determination of numerical FLCs which are compared with the experimental one.

BIAXIAL EXPERIMENTAL DEVICE

Biaxial testing machine and performance

In this work, a servo-hydraulic testing machine provided with four independent dynamic actuators is used. The center point of the specimen is always maintained stationary throughout the test by an efficient servo-hydraulic control. For each actuator, the loading capacity is $50KN$ and the maximum velocity can reach up $2m/s$. The load on each axis is measured by two specific gage sensors placed between the grip and actuator rod.

Cruciform specimen shape

In order to determine the forming limits under complex loading paths, a specimen shape has been defined. The main difficulty to design an appropriate cruciform specimen shape consists in forcing the onset of necking in the central zone and not in the arms of the specimen. Although cruciform specimens have been investigated quite extensively, no standard geometry exists to this day [2]. Moreover, for dynamic tests, the maximum stiffness of the specimen, the initial one, has to be adjusted according to the experimental setup capacities in order to control tensile test velocities. Other considerations like manufacturing constraints must also be taken into account.

To ensure that necking always appears in the central zone, the design of the cruciform specimens must induce the greatest deformations in this zone and no strain localizations in the other areas (grooves, fillets, ...). From finite element simulations, different specimen geometries have been investigated. The more effective and the more promising specimen shape has been optimized in order to make efficient its use for a whole forming limit curve identification [1]. The cruciform specimen shape obtained at the end of the optimization stage is presented Figure 1. For this geometry, the strain path value at the central point of the specimen is directly linked to the velocity ratio of actuators. At the end of the test, at the onset of necking, the strain path remains constant for all speed ratios. The linearity of the strain paths, obtained from the optimized geometry of the specimen, is illustrated Figure 2 for three different strain path values.

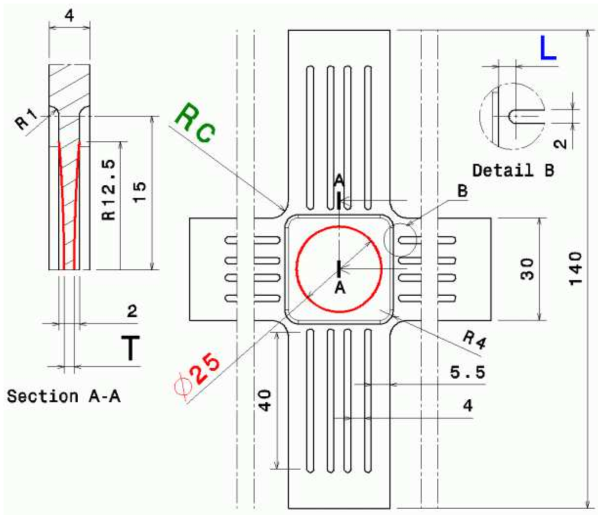

FIGURE 1. Specimen shape.

Strain measurement

The Digital Image Correlation technique (DIC) is used to evaluate the strain field during the experiments. To capture the consecutive images during the test, a Fastcam ultima APX-RS digital CMOS camera associated with a macro lens is used. The maximum acquisition rate is $3000i/s$ for a 1024×1024 pixels full resolution range. For the cruciform specimen geometry defined above, the dimensions of the filmed central zone are about $30 \times 30mm$. A resolution of

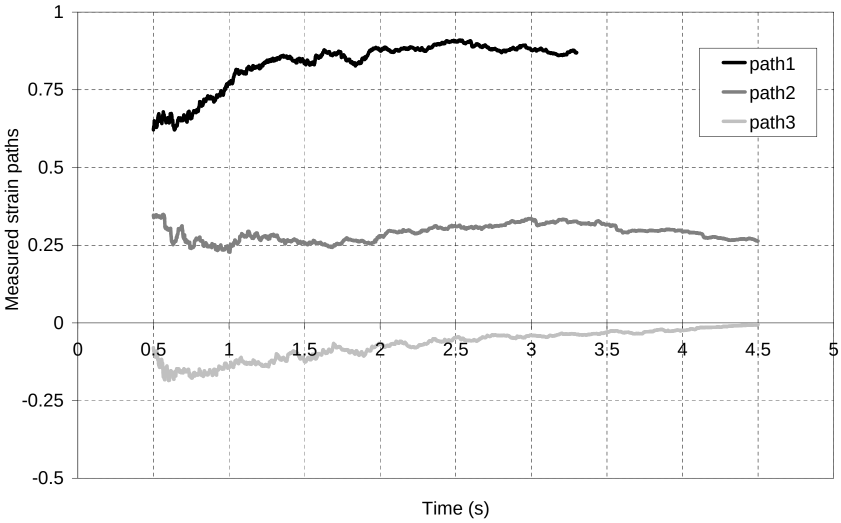

FIGURE 2. Measured strain paths.

512×512 pixels and an acquisition of 500i/s are used during the tests. The commercial digital imaging program CORRELA2006, developed by LMS at the University of Poitiers, is employed to perform correlation analysis in this work.

RHEOLOGICAL BEHAVIOR IDENTIFICATION

The elastic part of the aluminium alloy behavior is described by Hooke's model with Young modulus, $E = 67293MPa$, and Poisson ratio, $\nu = 0.3$. For the plastic part, an anisotropic Hill48 yield criterion is considered and the hardening behavior of the material is described by a Voces's law :

$$\overline{\sigma} = \overline{\sigma}_0 + \mathrm{Q}\sqrt{1 - \exp(-\mathrm{B}\overline{\varepsilon})} \tag{1}$$

where $\overline{\sigma}$ and $\overline{\varepsilon}$ are the equivalent stress and the equivalent plastic strain respectively, $\overline{\sigma}_0$ is the yield stress.

From experimental data and a FE model of equi-biaxial tensile tests, an inverse procedure of identification is carried out to determine the material parameters (constants of both hardening law and anisotropic yield criterion). The experimental data are the global force measurements on the two specimen axis and local displacements of two points (points 1 and 2) chosen in the central zone of the cruciform specimen (Figure 3). The best set of parameters is obtained by imposing experimental forces on the FE model and minimizing the difference in a least-square sense between the experimental displacements and the numerical ones. The commercial software packages ABAQUS and ModeFrontier are used respectively to simulate the equi-biaxial tensile test and for the optimization procedure. Table 1 shows the results of this identification. In order to validate the material identification based on biaxial experiments, material parameters obtained from the classical method which consists in testing three uniaxial specimens, in rolling, transverse and 45° directions are also presented Table 1.

TABLE 1. Identified material parameters of the Voce law.

Law	$\overline{\sigma}_0(MPa)$	$Q(MPa)$	B	F	G	H	N
Biaxial	134.3	342.6	2.7	0.723	0.662	0.338	1.545
Uniaxial	130.2	300.4	3.9	0.7	0.637	0.363	1.494

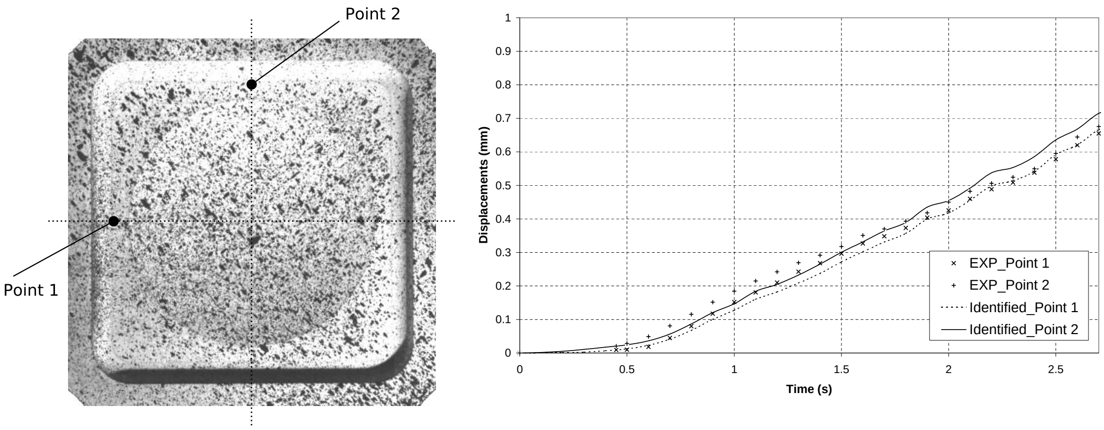

FIGURE 3. Experimental and simulated displacements of two points in the central zone of the biaxial specimen.

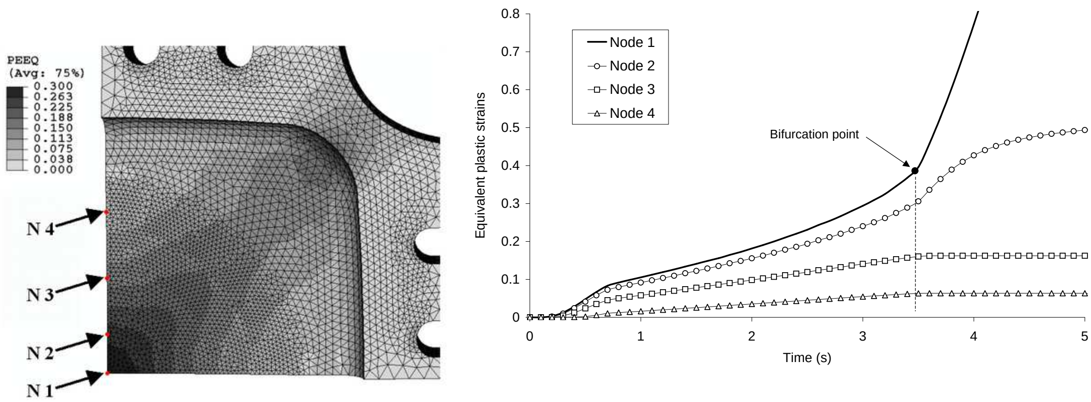

FIGURE 4. Evolution of the equivalent plastic strain for nodes 1 to 4 in the central zone of the specimen.

FLC IDENTIFICATION

For the numerical identification of forming limit curves, the main difficulty lies in the choice of an appropriate criterion to detect the onset of necking. Different failure criteria have been discussed by Zhang *et al* [3]. If the necking occurs in a zone, a sharp change of strain can be observed, corresponding to the onset of a plastic instability. Moreover, after the onset of this phenomenon, the level of strain remains constant in the other adjacent zones. This behavior can be observed by following the evolution of the equivalent plastic strain for different nodes in the specimen. To illustrate this phenomenon, the evolution of the equivalent plastic strain for four nodes (1 to 4) of the central zone of the cruciform specimen have been plotted Figure 4 for equi-biaxial conditions. An homogeneous evolution for these four curves is observed up to a moment of about t=3.5 s, after which the equivalent plastic strain for node 1 diverges rapidly compared to that of nodes 3 and 4. As expected, for these two nodes, the equivalent plastic strain remains constant after the onset of necking in the zone of node 1.

In this work, the criterion widely used in the M-K model studies is chosen to predict the onset of localized necking. When the equivalent plastic strain increment ratio between a point located in the necking zone (node 1) and a point in a adjacent zone (nodes 3 or 4) attains a critical value, the onset of localized necking is assumed to occur and the corresponding major and minor strains calculated at node 1 are retained as a point on the FLC. In the literature, this critical value generally varies from 7 [4] to 10 [5] and it is necessary to rigorously fix it for our specific geometry. From Figure 4, the plastic instability is clearly located with the evolution of the equivalent plastic strain at node 1 thanks to the onset of a bifurcation point at $t_{Bifurcation} = 3.4s$. We propose to plot the evolution of the equivalent plastic strain increment ratio between nodes 1 and 3 ($\Delta\bar{\varepsilon}^1/\Delta\bar{\varepsilon}^3$) and between nodes 1 and 4 ($\Delta\bar{\varepsilon}^1/\Delta\bar{\varepsilon}^4$). In order to apply this method for experimental identification of forming limit curves, the increment must not be calculated for a short time, otherwise many fluctuations associated with the accuracy of the experimental strain measurement could appear. The increment is calculated for a time of $1s$ and the results are plotted in Figure 5.

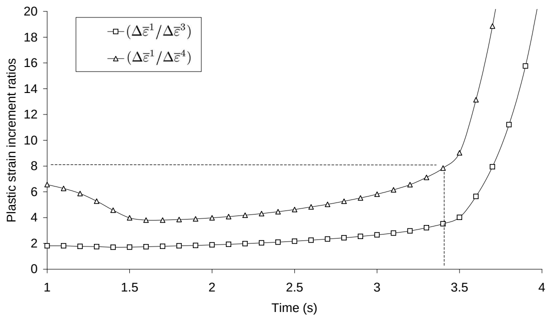

FIGURE 5. Evolution of the equivalent plastic strain increment ratios ($\Delta\bar{\varepsilon}^1/\Delta\bar{\varepsilon}^3$) and ($\Delta\bar{\varepsilon}^1/\Delta\bar{\varepsilon}^4$).

For the time corresponding to the onset of necking ($t_{Bifurcation}$), the critical values are identified for the two increment ratios. Afterwards, the higher and more sensible ratio $\Delta\bar{\varepsilon}^1/\Delta\bar{\varepsilon}^4$ will be used and a critical value of 8 seems to be appropriate to detect the onset of the bifurcation point and then the phenomenon of necking (Figure 5). For the time corresponding to the occurrence of necking, the numerical limit strain, i.e., the major and minor principal strains are calculated. Moreover, it is found that this critical value is well appropriate for the different speed ratios imposed on the two axes. To cover the whole forming limit diagram, the following speed ratios are tested : 1, 0.75, 0.5, 0.4, 0.25, 0.1, 0, -0.02, -0.1 and free for one axis. Then, a whole forming limit curve identified by use of this criterion can be plotted.

EXPERIMENTAL AND NUMERICAL FORMING LIMIT CURVE

The procedure described above is applied for the detection of both numerical and experimental forming limit strains. For the numerical ones, the Voce hardening law and the anisotropic Hill48 yield criterion identified either from biaxial experiments or uniaxial ones have been implemented in the FE model of the biaxial tensile test of the cruciform specimen. Figure 6 presents a comparison between the experimental and numerical formability of AA5086. One can see that the correlation, between experimental and numerical forming limit curves, is rather good, especially for the values of minor strain close to zero which is the zone of major interest for a FLC. The minimum of the FLC is not exactly reached for a zero value of the minor strain, this well known effect [5] is due to the non-linearity of the strain path at the beginning of the test. Figure 6 shows that the level of the numerical forming limit curve is sensitive to the identified material parameter values especially for the right hand side of the FLC. The numerical FLC from biaxial identification seems to be more precise that the one obtained from the three uniaxial tests. These results validate the identification procedure proposed in this work.

CONCLUSIONS AND PERSPECTIVES

The presented biaxial experimental device associated with a dedicated cruciform specimen is successfully used for a complete elasto-plastic characterization of the metallic sheet behavior of an aluminium alloy. The strain path controlled by displacements of actuators permits to cover the whole forming limit diagram. A good correlation between experimental and numerical results is shown, so the identified elasto-plastic behavior seems to be adapted for the

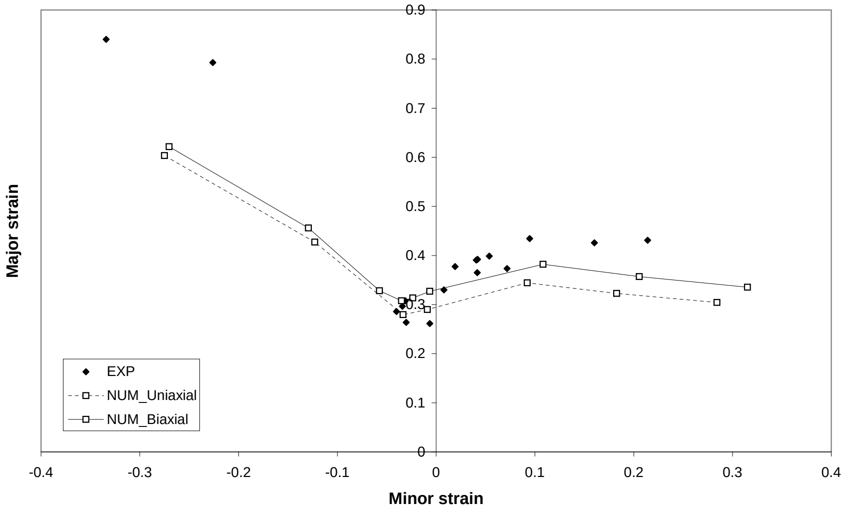

FIGURE 6. Experimental and numerical formability of AA5086.

numerical prediction of the forming limit curve, especially for large strains. The procedure, validated in quasi-static conditions, is now successfully adapted in dynamic ones in order to evaluate the influence of strain rate on formability.

REFERENCES

1. I. Zidane, L. Léotoing, D. Guines, and E. Ragneau, *Measurement Science and Technology* **21** (2010).
2. A. Hannon, and P. Tiernan, *Journal of materials processing technology* **198**, 1–8 (2008).
3. C. Zhang, L. Léotoing, D. Guines, and E. Ragneau, *Journal of Materials Processing Technology* pp. 3849–3858 (2009).
4. D. Banabic, S. Comsa, P. Jurco, G. Cosovici, L. Paraianu, and D. Julean, *Journal of Material Processing Technology* **157-158**, 23–27 (2004).
5. A. Barata Da Rocha, F. Barlat, and J. Jalinier, *Materials Science and Engineering* **68**, 151–164 (1984).